MEOR - A Low Cost Solution for Enhanced Waterflood Performance

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Introduction

Poor waterflood sweep efficiency due to varying permeability within an oil reservoir is a common problem. The high permeability areas of the reservoir tend to be quickly flushed with water while low permeability areas are bypassed. Many billions of barrels of known domestic oil reserves remain unrecovered due to poor waterflood efficiency. Hughes Eastern Corporation and Mississippi State University, through a DOE sponsored Class 1 Oil Project, have successfully demonstrated that waterflood recovery can be enhanced by proper stimulation of indigenous microorganisms within a reservoir.

Project Objective

The objective of this project is to demonstrate that waterflood sweep efficiency can be improved by restricting high permeability zones through growth of indigenous bacteria so that water is diverted to low permeability zones which have been inefficiently waterflooded. The successful development and nationwide application of the microbial enhanced oil recovery (MEOR) technology could result in recovery of billions of barrels of bypassed oil which are now either unrecoverable or only recoverable at much higher cost.

Field Description

The field chosen for demonstration of the technology is the North Blowhorn Creek Oil Unit which is located in Lamar County, Alabama, about 75 miles west of Birmingham in the Black Warrior Basin producing region. The oil reservoir is the Carter sandstone of Mississippian age. The reservoir depth is about 2300' and the temperature is 90° F. The relatively clean but well compacted sand has an average porosity of 12%, an initial water saturation of 21% and a permeability varying from about one millidarcy to several hundred millidarcies. Initially a saturated oil reservoir with a primary gas cap, the reservoir held about 16 MMBO in place. The trapping mechanism is stratigraphic. Primary recovery was by depletion drive with no natural water influx. After discovery in 1979, the reservoir was developed on 80 acre spacing. Due to rapid depletion and a recognized need for secondary recovery, the field was unitized in 1983 and infill drilled on 40 acre spacing. Water injection began in late 1983. The reservoir responded very favorably to the waterflood, reached peak production of 85,000 BOPM in 1985 and then began declining in 1986. The current production rate is 8100 BOPM, 1200 MCFM and 90,000 BWPM. The waterflood injection rate is 104,000 BWPM. There are currently 23 active producing wells and 18 active injectors. The reservoir cumulative production through March 1999 was 5.82 MMBO, 3.2 BCF and 14.7 MMBW. The cumulative injected water was 22.3 MM bbls. Figure 1 is a net pay isopach showing the field geometry, the well locations and injection patterns.

MEOR Project Description

The microbial enhanced oil recovery project is organized in three phases. Phase I is the planning and analysis phase which lasted nine months and has been completed. Phase II is the field implementation phase which began in the fourth quarter of 1994 and has been completed. Phase III is the technology transfer phase which began in July 1998 and is now being concluded.

Phase I consisted of drilling and completing two new wells to obtain fresh cores and production data, special handling and analysis of the cores, a tracer study to determine fluid travel times and the collection of baseline data. The NBCU 34-6 No.3 was drilled in March 1994 and encountered 20 feet of net Carter oil sand. The well was completed and placed on rod pump at an initial rate of 25 BOPD and 1 BWPD. Current production is about 85 BOPD and 22 BWPD. The NBCU 34-3 No.2 was drilled in April 1994 and penetrated 21 feet of net pay sand. The core recovered from this well appeared to be unswept by the waterflood and contained a high saturation of bypassed oil. The well was completed, placed on rod pump and initially tested 43 BOPD and 43 BWPD. Recent production is about 5 BOPD and 180 BWPD.

One-foot sections were obtained as the core was removed from the core barrel. The sections were quickly transferred to special containers for transportation and storage in an oxygen-free environment. Core plugs were cut in a nitrogen environment and mounted in a special holder for core flooding tests to determine microbial nutrients to be used in the field. Other pieces of core were crushed into a fine powder to be used in determination of the microbial population. The laboratory testing was done to confirm four things: 1) that indigenous microbes were indeed present in the reservoir rock; 2) that the microbes could be stimulated to grow using the proper inorganic nutrients; 3) that flow through the cores could be restricted as a result of the microbial growth; and 4) a nutrient injection protocol could be developed for scale-up to field applications.

A radioactive tracer survey was performed in the first test pattern prior to start of nutrient injection. A tritiated water tracer (2 Ci) was injected into the 2-14 No.1 injection well to determine the fluid travel times to the producers in the pattern and thus give some indication of the minimum time required for detection of microbial activity. The tracer was injected on 4/27/94 and first detected in the 2-13 No.1 on 10/12/94. The tracer peaked in this well in January 1995. Tracer was detected in the 11-3 No. 1 in October 1995. Therefore, the minimum time required for flood water to travel to the highest rate offset producer is about six months. The time required for microbial growth to occur and result in increased production could easily be two or three times the fluid migration time.

Baseline data acquisition began during Phase I and continued during Phase II. Data was collected on four test patterns and four control patterns (shown as TP #1-4 and CP #1-4 on Figure 1). Fluid production and injection rates were stored in a data base and plotted frequently to scan for changes. In addition, water samples were analyzed for mineral and microbial content on a monthly basis. Oil samples were analyzed by gas chromatograph to look for shifts in hydrocarbon composition which may indicate microbial degradation of heavier hydrocarbons or that previously unswept oil was being recovered. Oil viscosity and gravity data were also collected on each producing well in the test and control patterns.

Phase II was the field implementation part of the MEOR project. Based upon the successful results of the laboratory waterflooding tests, a nutrient injection schedule was established for each of the four test pattern injectors. A three-day-a-week repeating schedule was established which consisted of injection of potassium nitrate every Monday and monosodium phosphate on Wednesdays and Fridays. In test patterns 2 and 4, molasses was substituted instead of monosodium phosphate on Wednesdays to test the effect of injecting an organic nutrient. Molasses were later added to test patterns 1 and 3.

Four nutrient injection skids were constructed as shown in Figure 2. The pump skids had to have the capability of mixing 50-300 lbs. of dry chemical with 200 - 300 gals/day of water and pumping the resulting solution at a constant rate over a 24-hour period at 1300 psi discharge pressure. The skids had to be simple, easily maintained and of rugged construction for operation by field personnel. The mixing hopper is an improvised design which takes advantage of the available 1200 psi waterflood water to jet mix the dry chemicals. The holding tank is a 300 gallon polypropylene tank of the type often used for oilfield chemicals. An electric mixer allows for stirring to insure that all the chemical goes into solution. The pumps selected were Cat Model 231 triplexes which are belt driven by DC motors with rheostat controls.

Nutrient injection was begun into the 2-14 No.1 well on 11/21/94. The waterflood injection rate was approximately 475 BWPD. Construction of the remaining three skids and initiation of injection into the other test patterns was delayed in order to allow time for mechanical evaluation of the equipment as well as time to detect any near-wellbore injectivity problems. No problems were encountered, so the remaining pump skids were completed in January 1995. Nutrient injection into 11-5 No.1 was begun on 1/16/95 and into 2-6 No.1 and 34-9 No.2 on 2/27/95. No significant injectivity or mechanical problems developed.

Three additional wells were drilled and completed in the Fall of 1996. The main purpose of the three wells was to obtain core data which would confirm whether or not nutrients were being widely dispersed into the reservoir and the effects of the nutrients on microbial growth. The first of the three wells was NBCU 2-5 No. 2 which was drilled near the boundary between Test Pattern 4 and Control Pattern 1 (Figure1). The well encountered 24 ft. of net Carter pay sand. The core analysis indicates that, as a general rule, the lower permeability rock retains a higher oil saturation while the high permeability rock is better swept resulting in lower oil saturation. Visual observation of the core indicated much remaining oil in the low permeability rock. The well was cased, perforated, fracture stimulated and placed on production.

The second of the Phase II wells to be drilled was the NBCU 2-13 No. 2 which was drilled northwest of Test Pattern 1. The well found 21 ft. of net Carter pay sand. The core analysis indicated much higher permeability in the upper ten feet of the sand than in the lower portion and, as in the previous well, the higher permeability rock generally has lower oil saturation than the lower permeability rock which is harder to sweep by waterflood. The well was cased, perforated and placed on production without fracture stimulation.

The third well drilled was the NBCU 2-11 No.3 which was drilled within Test Pattern 4 and within 500 ft. of the 2-6 No. 1 nutrient injector. The well encountered 36 ft. of Carter pay sand which was twice the anticipated thickness. A 32 ft. core was recovered which revealed significant remaining oil saturation, along with some portions which had obviously been swept by the waterflood. It was anticipated that the water swept sections would provide the best opportunity to observe microbial growth as a result of nutrient injection into the nearby 2-6 No. 1 well. The well was cased, perforated, fracture stimulated and placed on production.

The chemical and microbiological analyses of the cores from the three new wells was begun immediately by Mississippi State University. Ten sections of core from each well were stored anaerobically while six sections were stored under aerobic conditions. Initially five sections of core from each well were examined for the presence of nitrate ions and phosphate ions. Nitrate ions were present in four of the five sections from well 2-5 No. 2, three of the five sections from well 2-13 No. 2 and all five sections from well 2-11 No. 3. Phosphate ions were present in three of the sections from well 2-5 No.2, none of the sections from 2-13 No. 2 and one of the sections from well 2-11 No. 3.

Electron microscopic examinations of the four core sections from well 2-5 No. 2 revealed many microbial cells in three of the sections. Shown in Figure 3 are some of the representative SEM photographs. The large numbers of bacteria are obvious. The large numbers are in sharp contrast to the number seen in cores from the NBCU 34-3 No. 2 drilled at the beginning of the project.

Results

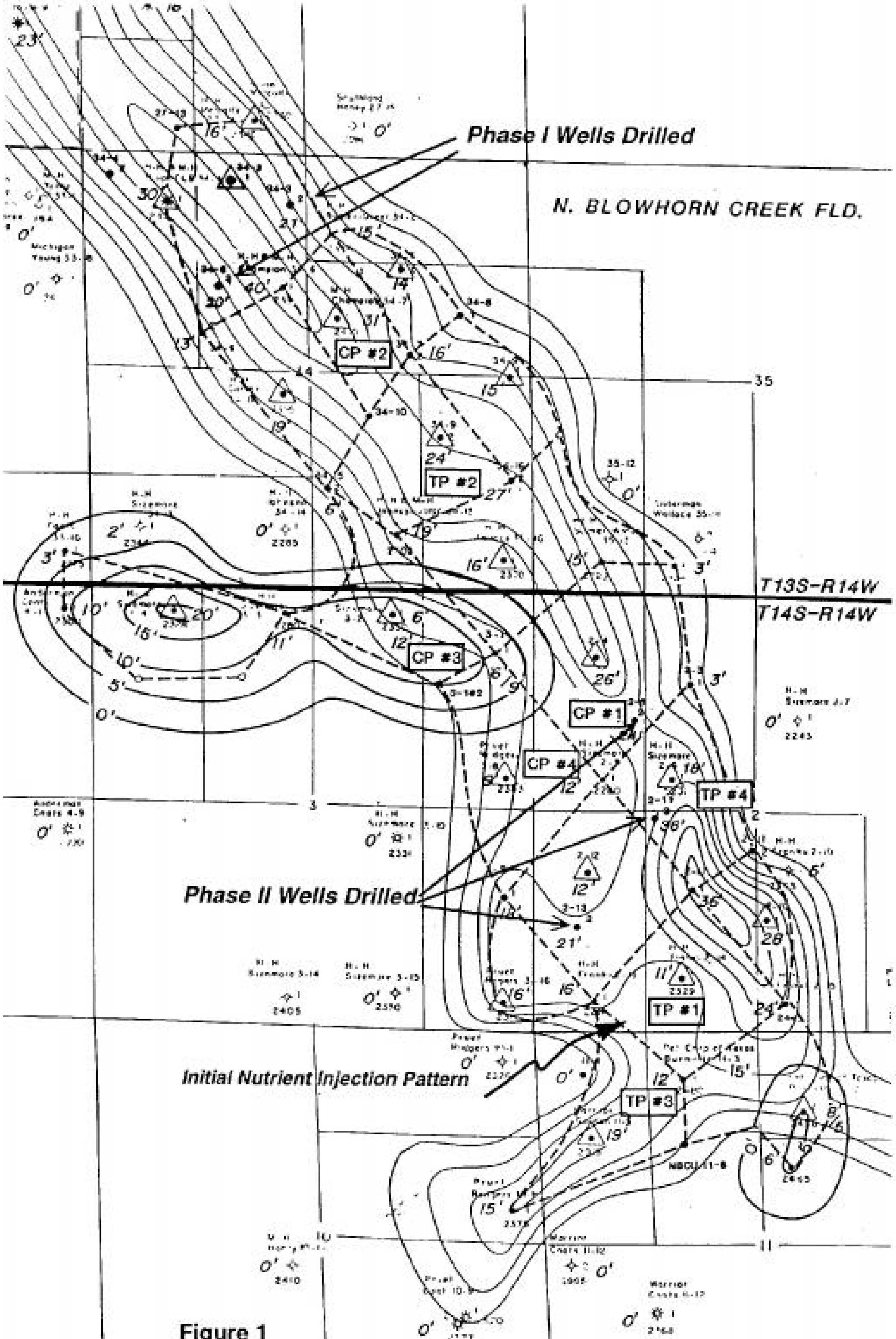
As of April 1997, eight out of fifteen test pattern wells had positive responses to the nutrient injection. Because of this success, the project was expanded to include six more nutrient injectors with hopes of further improving the MEOR response. By July 1998, after forty-two months of nutrient injection into four wells and only twelve months of nutrient injection into six wells, the performance had improved in twelve out of nineteen wells, or sixty-three percent. The performance of selected wells is seen in Figures 4 through 9.

By the end of 1998,incremental production due to the new wells drilled and the MEOR response was 161 MBO. Of this incremental, 92 MBO was due to new drilling and 69 MBO was due to MEOR (see Figure 10). The production decline rate had been reduced from 18.9%/yr prior to the project to between 7 and 12%/yr. Thus the remaining incremental reserves are between 434 MBO and 863 MBO based upon an abandonment rate of 1500 BOPM. The field life has been extended by a minimum of 53 months.

Economics and Benefits

Economics of the MEOR process were calculated by excluding all costs associated with the additional well drilling and costs of laboratory testing and documentation for DOE. The total cost of nutrients, engineering, field labor and injection skid LOE was $658,000. The ultimate MEOR incremental reserves were estimated to be 499 MBO. Thus the incremental cost per barrel was $1.32. The incremental cost of MEOR production recovered through the end of 1998 was $9.54/bbl, thus the reserves recovered to date have already paid the cost of nutrient injection.

The MEOR technology employed in this project has proven successful and should have broad applicability across the nation. The process should work in any waterflood field having permeability variations. The technology should not be limited to sandstones, but should work in carbonates as well. The U. S. DOE has estimated the proven residual oil resource in the U. S. to be about 350 billion barrels. It is estimated that 50% of current domestic production comes from waterflooded fields and that somewhere between 50 and 75% of all fields have been or will be waterflooded. If MEOR can result in recovery of just 10% of the residual oil in waterflooded fields, the potential is about 20 billion barrels. If the additional recovery is 15% of residual oil, the potential is about 30 billion barrels, or roughly equal to the DOE's estimate of remaining economically recoverable domestic reserves.



Phase I Wells Drilled
N. BLOWHORN CREEK FLD.
CP #2
TP #2
T13S-R14W
T14S-R14W
CP #3
CP #1
CP #4
TP #4
Phase II Wells Drilled
TP #1
Initial Nutrient Injection Pattern
TP #3
NET PAY ISOPACH

Figure 1

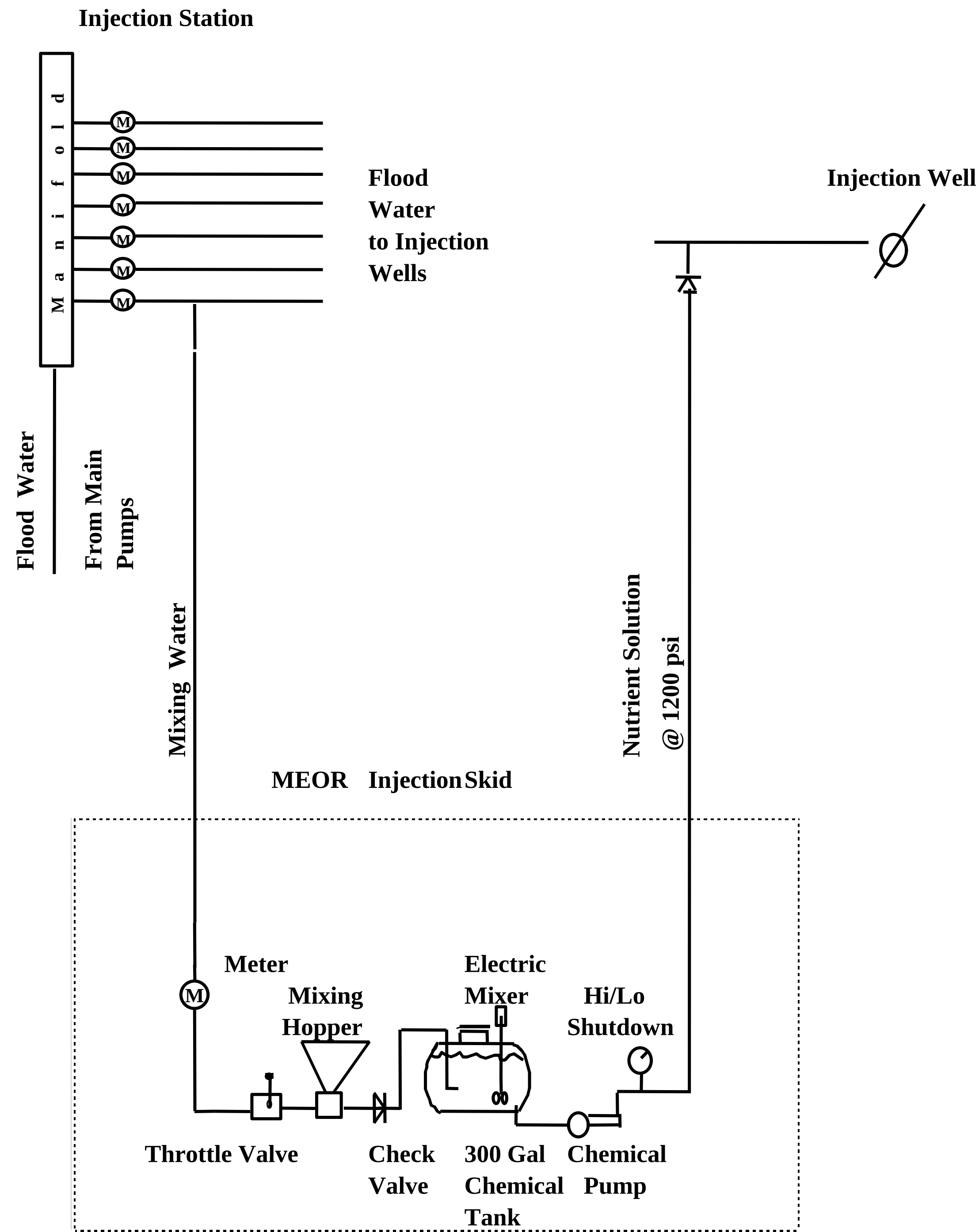


Figure 2: Flow Diagram for North Blowhorn Creek Unit MEOR Injection System

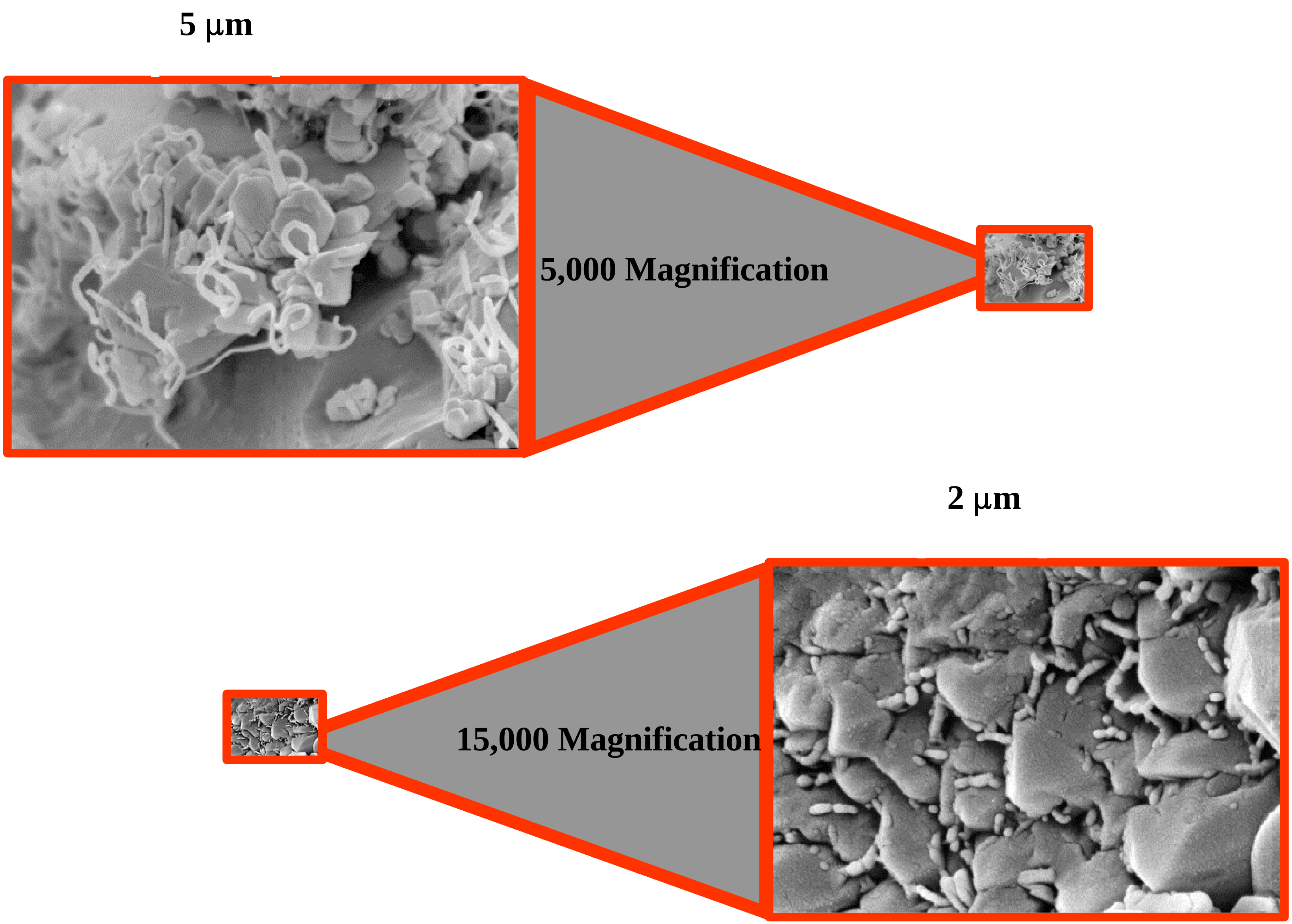


Figure 3. Photographs of microorganisms in cores from two newly drilled wells as seen using the electron microscope.

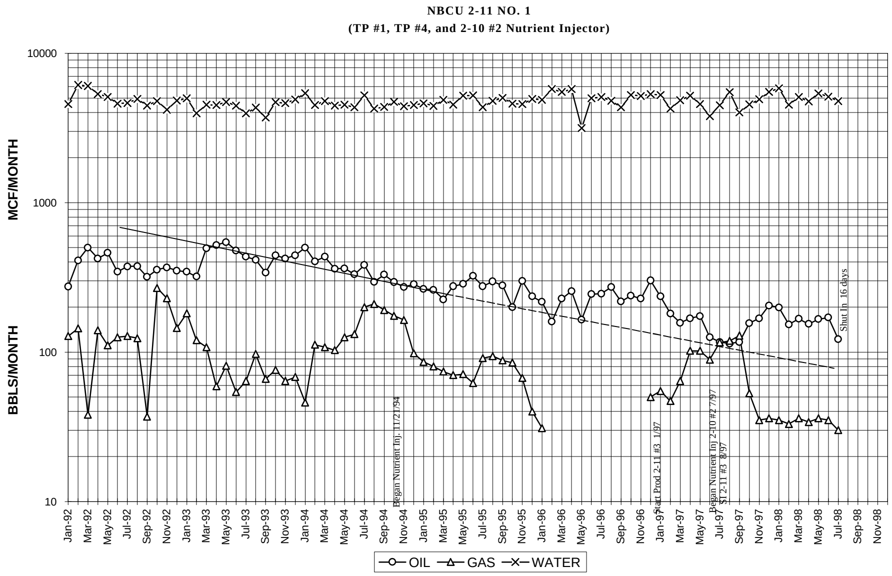


Figure 4: A production response began in this well about 5 months after starting nutrient injection in offset injector.

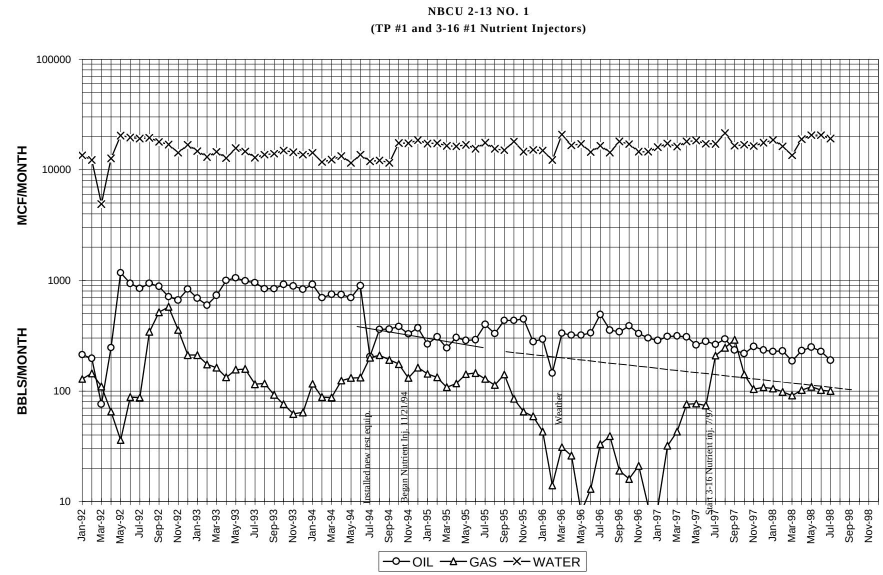


Figure 5: A significant production increase occurred about 7 months after starting nutrient injection in offset injector.

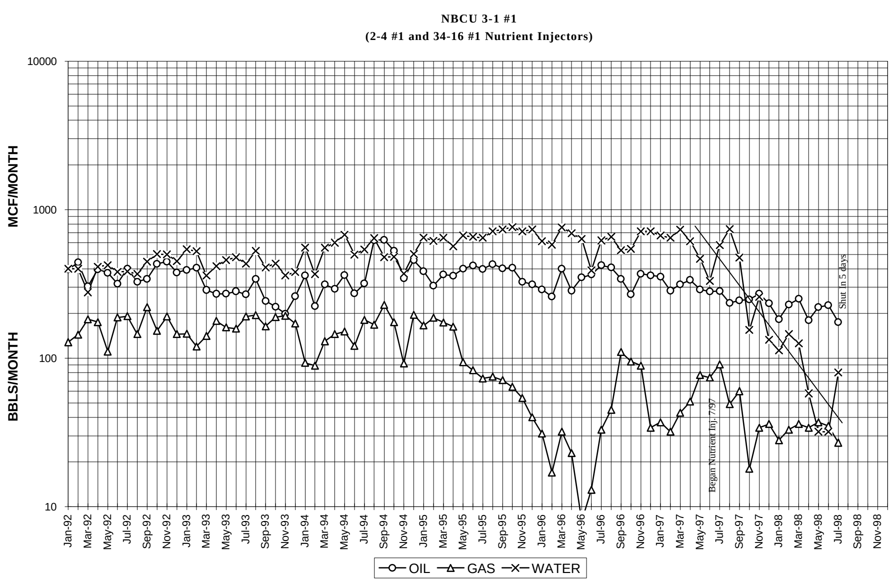


Figure 6: Note sharp decline in water production after 3 months of nutrient injection.

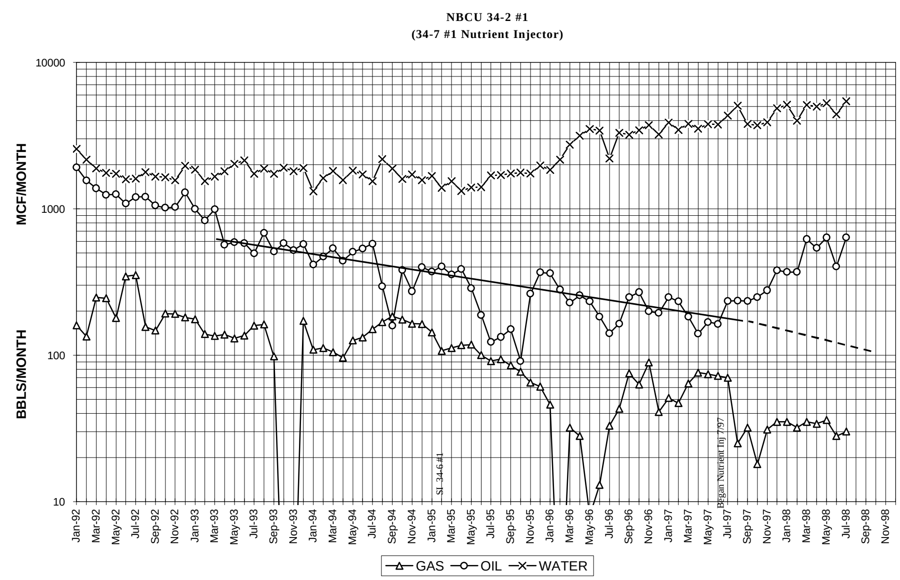


Figure 7: Production increased dramatically within 4 months of starting nutrient injection in offset injector.

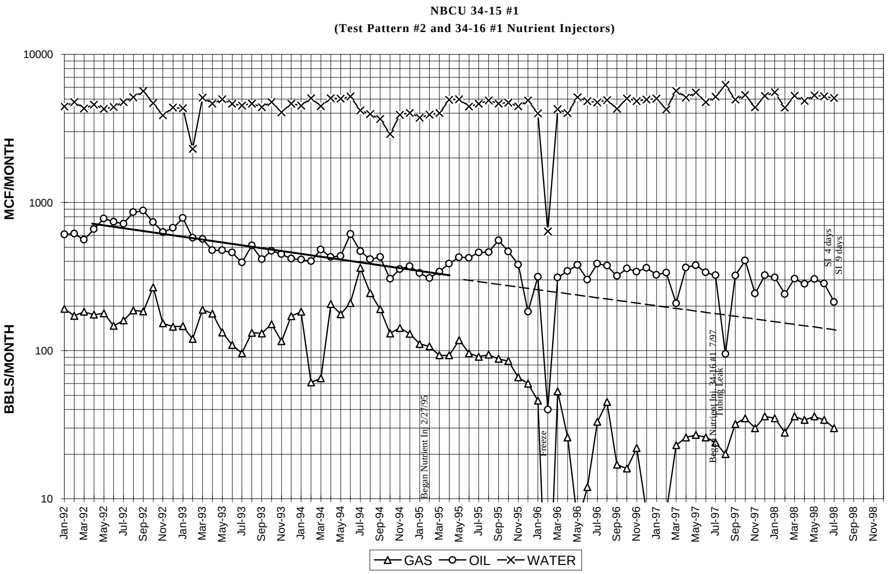


Figure 8: Note sustained change in decline slope as a result of MEOR response.

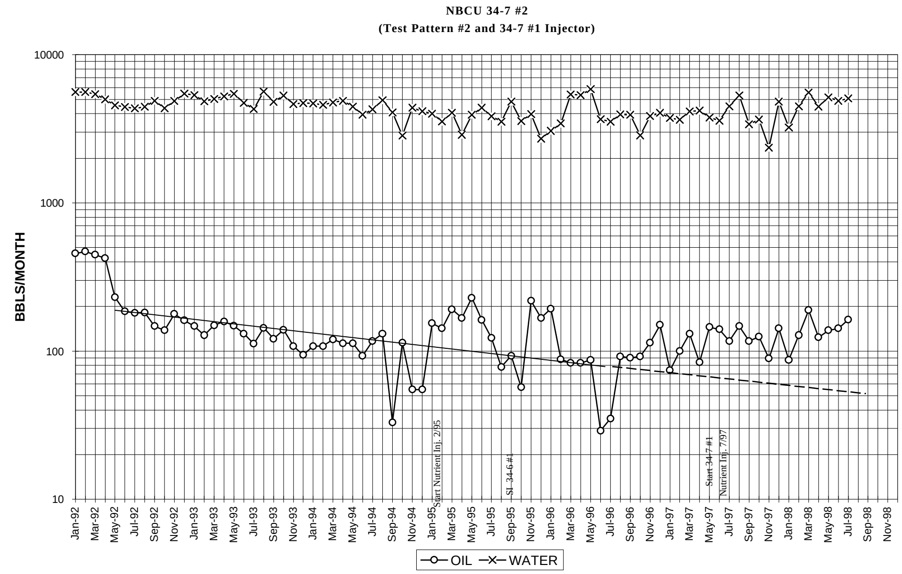


Figure 9: Two production responses are seen here, one after nutrient injection began in 1995 and another when Second offset nutrient injector began in 1997.

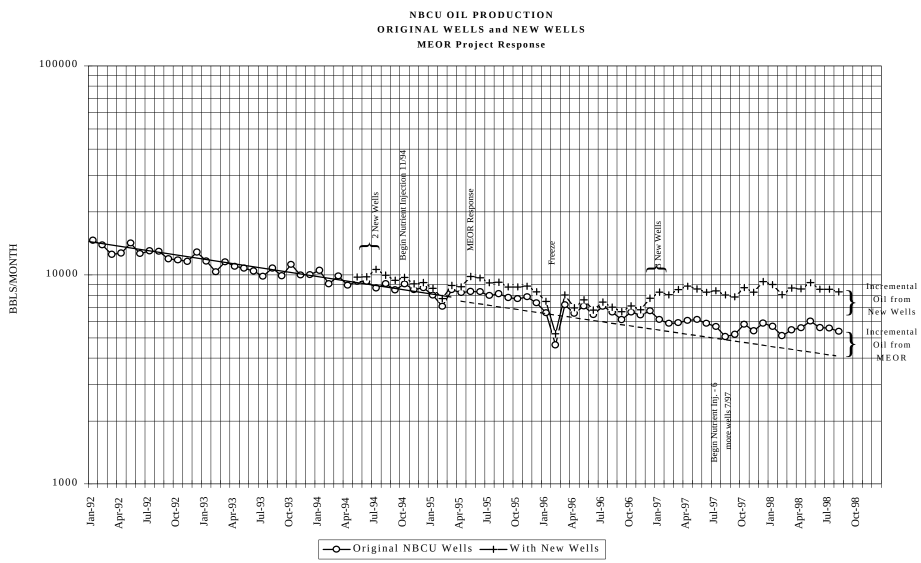


Figure 10: Field wide response to MEOR compared to baseline projection.